

# ON THE INTRACLUSTER MEDIUM IN COOLING FLOW & NON-COOLING FLOW CLUSTERS\*

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**Abstract** Recent X-ray observations have highlighted clusters that lack entropy cores. At first glance, these results appear to invalidate the preheated ICM models. We show that a self-consistent preheating model, which factors in the effects of radiative cooling, is in excellent agreement with the observations. Moreover, the model naturally explains the intrinsic scatter in the L-T relation, with “cooling flow” and “non-cooling flow” systems corresponding to mildly and strongly preheated systems, respectively. We discuss why preheating ought to be favoured over merging as a mechanism for the origin of “non-cooling flow” clusters.

**Keywords:** Intracuster Medium, Sunyaev-Zel’dovich Effect, X-rays, Entropy Profiles

## 1. Introduction

Correlations between the various X-ray and Sunyaev-Zel’dovich Effect (SZE) properties of galaxy clusters offer important clues into the physical processes that have impacted the intracuster medium (ICM). Observed scaling relations have been shown to deviate significantly from expectations based on numerical simulations and analytic models that only take into account the influence of gravity on the ICM. Such discrepancies have prompted considerations of additional, previously unexamined, gas physics. One model, the preheating model, explores the possibility that the nascent ICM is heated by galactic winds and/or AGN outflows from galaxies existing at the time. Even in its simplest avatar, the model scaling relations, be they SZE v. SZE, SZE v. X-ray or X-ray v. X-ray, are in remarkable agreement with the observations (cf. [1–3]). However, recent X-ray data from *XMM-Newton* and *Chandra* suggests a potential prob-

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lem with the model. Preheating of the ICM sets an entropy floor that manifests itself as a central core-like structure in the entropy profile. A number of observed profiles show no such cores. Although we recognize that the current set of published Chandra and XMM-Newton cluster results are biased in favour of “massive cooling flow” systems or active mergers, the very existence of systems with power-law-like entropy profiles needs addressing.

Here, we briefly report on our efforts to understand this particular issue, and its implications for the preheated model. Our investigations involve a re-examination of the assumptions underlying the theoretical model as well as of the observational evidence for and against the model.

## 2. Re-examining the Theoretical Model

Most preheating models are incomplete in that they do not take into account radiative cooling (cf. [1]). While preheating lowers the efficiency of cooling, it does not mitigate it entirely and over a Hubble time, the effects of cooling can be significant. Several recent studies, [4, 5], have highlighted the potentially important role of cooling though not necessarily in the context of a preheated model. Traditionally, cooling has been difficult to model. However, we have developed a fast, efficient scheme for doing so. The scheme can factor in the effects of not only preheating and radiative cooling (due to both line and continuum emission) on the ICM over cosmological timescales, but potentially also those due to other processes such as conduction. The scheme is currently being tested against detailed hydrodynamic simulations and the initial results are very encouraging. A detailed description of this scheme will be forthcoming. Here we present some early results for the preheated+cooling model.

## 3. Cluster Entropy Profiles: Theory and Observations

Figure 1 shows the effects of varying levels of preheating+cooling on cluster entropy profiles. Radiative cooling is very efficient in clusters subjected to low levels of preheating. It causes the central entropy core to disappear on a relatively short timescale and drives the entropy profile into the  $r^{1.1}$  power-law form reminiscent of the observed profiles of “cooling flow” (CF) clusters. In contrast, cooling is much less efficient in clusters with highly preheated ICM.

We have assembled a preliminary collection of observed entropy profiles in order to see how these compare to the model results. We find, suprisingly, that the observed entropy profiles are not all self-similar and power-law-like, but span the entire range of shapes seen in Figure 1.

## 4. Reconstructing the Scaling Relations

Figure 2 shows  $L_X - T_X$  relation for preheated+cooling clusters subjected to varying levels of preheating and observed 10 Gyrs later. Also plotted are

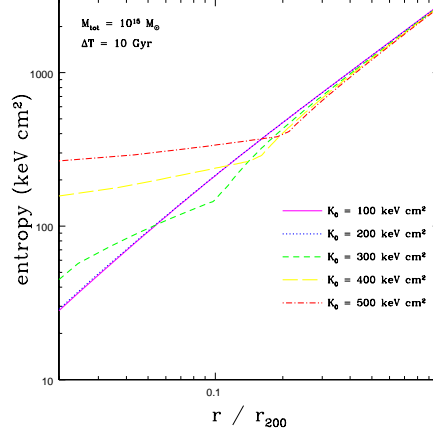


Figure 1. Entropy profiles of a  $10^{15} M_{\odot}$  cluster preheated to different values of  $K_0$  and observed after 10 Gyrs. The efficacy of radiative cooling increases with decreasing  $K_0$ . In clusters with low  $K_0$  values, cooling rapidly erases the central core and drives the profile into a  $r^{1.1}$  power-law, reminiscent of the observed “cooling flow” clusters profiles. Intriguingly, entropy profiles of actual clusters span the entire range of profile shapes shown.

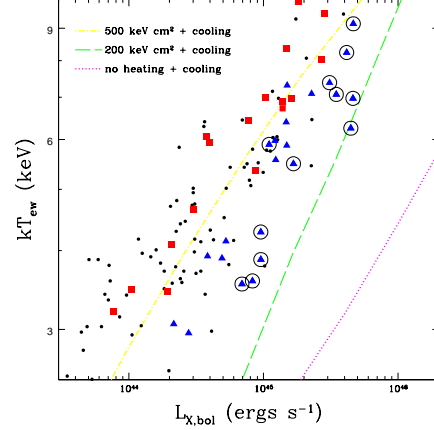


Figure 2. The  $L_X - T_X$  relation for  $z < 0.2$  clusters constructed using the actual observed values, as opposed to “cooling flow corrected” quantities. Within this locus, we identify the locations of known “cooling flow” and “non-cooling flow” clusters (see text for details). We also show the  $L_X - T_X$  results for the preheated+cooling model. We identify NCF and mCF systems with high and low  $K_0$  values, respectively.

the  $(L_X, T_X)$  for  $z < 0.2$  clusters from Horner’s ASCA Cluster Catalogue [6]. Unlike the data typically used in the construction of such plots, this set is *not* “cooling flow corrected”. This is important. The theoretical values incorporate the effects of cooling; therefore, a fair comparison with the observations requires that we use data of comparable character.

Both the corrected and the uncorrected data exhibit the same correlations, though the latter has larger scatter. This is well known. However, the scatter is not random. Based on features in the temperature and X-ray SB profiles, we have classified clusters as non-cooling flow clusters (NCF - squares), ordinary cooling flow clusters (CF - triangles), or massive cooling flow clusters (mCF - circled triangles). Although most clusters remain unclassified, it is readily apparent that NCF systems lie close to the upper-left edge of the band while the mCF clusters delineate the opposite (lower-right) edge.

Comparing the preheated+cooling model predictions against the observations, we find the two in excellent agreement. However, in order to account for the breadth and structure within the observed  $L_X - T_X$  band, we have to abandon our previous *ad hoc* assumption of uniform energy injection across the entire cluster population. Within our framework, the NCFs correspond to

strongly preheated systems ( $K_o \sim 400\text{--}500 \text{ Kev cm}^2$ ) while the mCFs correspond to mildly preheated systems ( $K_o \sim 100\text{--}200 \text{ Kev cm}^2$ ).

## 5. Non-Cooling Flow Clusters: Products of Preheating?

The assertion that NCF systems are strongly preheated clusters runs counter to the prevailing view. In the latter, NCFs are identified as clusters whose cool dense gas cores, the source of the excess central X-ray emission characteristic of the CF clusters, have been disrupted by major mergers. Images of NCFs with disturbed X-ray morphologies are often used to support this scenario. However, there are numerous CF systems that also appear to be in the throes of on-going mergers. Perseus is one such example [7]. The ubiquity of mergers argues against them being the cause of the differences between CFs and NCFs.

To test our hypothesis, we have carried out a series of numerical simulation experiments. One distinguishing feature of our study is that our simulations include radiative cooling. Preliminary results suggests that even for nearly head-on 3:1 mergers, variations in the X-ray observables of the primary cluster are extremely short-lived. In particular, we find that if the primary starts out as a CF-like system, by the time the merger remnant has been assimilated, it will have regained its CF-like character. Motl et al. [8] too get similar results. These findings argue that there ought *not* to be any dynamically relaxed NCF systems. But there are: eg. A1413, A1651, A2319, A3158. That such systems exist at all further indicates an alternate origin for the CF/NCF clusters.

To reiterate, a self-consistent model of the ICM that factors in radiative processes and allows for cluster-to-cluster variations in the level of initial preheating not only is able to account for the existence and the properties of CF and NCF clusters, but also of those that are between these two extremes.

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